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Developments in the Measurement and Estimation Methods for Cement Clinker Quality Parameters

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***Abstract*— The workability and strength of cement depend on the quality of the clinker produced from the rotary kiln. The quality of the clinker is dependent on the values of parameters such as the lime saturation factor (*LSF*), silica moduli (*SM*), alumina moduli (*AM*), alite (*C_3S*), etc. This paper critically appraises the current measurement and estimation methods for cement clinker quality parameters. On the one hand, the review shows that the current online hardware sensors can only handle a small sample of clinker per analysis. Moreover, the existing online analyzers (hardware sensors) are expensive to install and lack backup sensors in case they are faulty, down for maintenance or replacement. On the other hand, the review shows that soft (model or software-based) sensors are capable of offering solutions to some of the challenges of the online hardware sensors. However, their predictions depend on the hardware sensors for some input data and the available cement rotary kiln models are not in the form suitable for online estimation of clinker quality parameters. It is concluded that real-time measurement/estimation and control of clinker quality parameters is still a challenge in the cement manufacturing industry. It is therefore recommended that soft sensors should be introduced to complement the online hardware sensors.**

Keywords*— Cement, quality parameters, clinker, soft sensor, online, hardware sensor.

I. INTRODUCTION

Cement is produced from raw materials such as limestone (a source of lime), clay (a source of silica), laterite (a source of iron) and red ochre (a source of aluminum). The process for cement manufacturing can be wet or dry. Cement production using dry process involves three fundamental stages which are: preparation of the raw materials, production of the clinker and preparation of the cement. The first step in the production of cement is usually the preparation of the raw materials. These raw materials are quarried from local rocks, after which they are loaded into large trucks for transportation to the crushing plant. Through crushing and screening operations, the raw materials are reduced to acceptable size after which they are fed into a vertical roller mill where they are further ground and mixed in the required proportion (or composition) referred to as raw meal (kiln feed). The raw meal are then stored in large silos until required for clinker production. In the second step, the required size raw meal enters a multistage cyclone preheater where it is preheated by the hot flue gas coming from the cement rotary kiln. Bulk of the calcination (decomposition of $CaCO_3$) of the raw meal is done in the multistage cyclone preheater. The preheated raw meal then enters the cement kiln. In the rotary kiln, the different components present in the raw meal, at high temperature, react with one another other. The lime (CaO) reacts with other components like silica, alumina and iron oxide present in the raw meal to form complexes of dicalciumsilicate (C_2S), tricalciumsilicate (C_3S), tricalcium aluminate (C_3A) and tetracalciumaluminoferrite (C_4AF). These reactions result in a final nodular product known as clinker. To maintain product quality, all these components must be maintained in the required proportions in the clinker. The unreacted lime appears as free lime in the clinker and should be limited to a minimum. The hot clinker is then discharged into clinker cooler where some of the heat is recovered and returned to the multistage preheater. The cooled clinker is stored in clinker silos until required for cement production. Finally, the clinker is ground with a small amount of gypsum and other additives in the cement mill to form the final product (cement). Cement is stored in cement silos, after which are shipped in bulk or bags and distributed to customers. In the chemical analysis of cement, the parameters that define the quality of the clinker are: lime saturation factor (LSF), silica moduli (SM), alumina moduli (AM), etc. [1].

LSF is the ratio of the actual amount of lime to the theoretical lime required by the other major oxides in the clinker. LSF greater than100% means that the clinker contains some free lime. Aldieb and Ibrahim [1] reported that, for technical purposes, good values of LSF range between 80% and 95%. SM is the proportion of SiO_2 to the total of Al_2O_3 and Fe_2O_3 present in the clinker. The amount of melt phase in the burning zone is a function of the silica moduli.
Increasing silica moduli impairs the burnability of the clinker by reducing liquid phase content and tendency toward formation of coating in the kiln. Also, increasing silica moduli causes a slow setting and hardening of the cement. Silica moduli is reported in [1] to range between 1.9 and 3.2.

AM characterizes the clinker by the proportion of alumina to iron oxide. It determines the composition of liquid phase in the clinker. Alemayehu and Sahu [2] reported that, when AM is lower than 1.5, both oxides are present in their molecular ratios and therefore only tetracalcium aluminoferrite can be formed in the clinker; consequently, the clinker cannot contain tricalcium aluminate. This is the case called Ferrari-cement which is characterized by low heat of hydration, slow setting and low shrinking [1]. Alumina moduli is reported [1] to be in the range from 1.5 to 2.5. Free lime (FCaO) is the

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amount of unreacted lime free in the clinker. The lower the free lime the closer the reactions are to completion. However, too low free lime can also indicate too hard and uneconomic burning. Over burning the clinker, wastes fuel, stresses refractories, increases the power required for cement milling, and reduces cement strength. The free lime target is typically between 0.5% and 2.0% [3]. Cement manufacturers are gradually becoming aware of the need for real-time measurement and/or estimation of clinker quality parameters during product quality assessment. Cement clinker quality parameters are mostly measured by offline laboratory analysis or by the use of online analyzers. The measurement delay and cost associated with these methods are a concern in the cement industry. Therefore, this paper reviews the current measurement and estimation methods of clinker quality parameters. The findings are expected to aid in the decision making to improve the measurement and control of clinker quality parameters during cement production.

II. PROCESS MEASUREMENT AND CONTROL WITH HARDWARE SENSORS IN CEMENT MANUFACTURING PLANT

In cement manufacturing plants, instrumentation equipment such as (hardware) sensors, controllers and actuators are essential for proper plant operation. Some hard ware (sensors) are used to detect easily measurable parameters such as temperature, pressure, level, flow, etc., while others in the form of online analyzers are used for detecting the difficult to measure process or quality parameters. On the other hand, controllers and actuators are used to maintain the detected conditions.

Online quality control of cement requires that the mineral contents of cement and clinker such as C_3S, C_2S and free lime be measured real time. Online analyzers that apply X-ray fluorescence (XRF) and/ or X-ray diffraction (XRD) techniques are normally used to ensure quality control in the cement manufacturing process.

A. X-Ray Fluorescence

The X-ray fluorescence technique (XRF) is used to perform chemical elemental analysis on cement raw mix. From this analysis, concentrations for the major oxides are derived. Since mineralogical information is not available from XRF spectra [4], these measured compositions are further used to calculate the hypothetical compositions of clinker phase minerals using the Bogue equations [5]. However, the equations are based on the assumption that thermo-dynamic equilibrium is achieved in the kiln, and this is not always the case. The implied phase compositions can vary enormously (up to 20% for C_3S) compared to actual composition, depending on kiln conditions and minor elements [6].

B. X-Ray Diffraction

X-ray diffraction (XRD) is a common technique for measuring mineral content. The technique involves firing an X-ray beam onto a sample and then measuring its diffraction pattern. When X-rays are fired onto a crystalline material they are reflected in all directions. However, as they reflect off each layer of the crystalline lattice, there are certain angles for which the reflected X-rays are in phase and the signal will be very strong. At other angles, they are out of phase and the X-rays cancel each other. This process of cancellation and reinforcement is called diffraction. The angle at which the diffracted rays are in phase is related to the distance between the lattice planes, creating a pattern that is characteristic for a particular mineral. Most XRD analyzers are laboratory based [6]. A sample is collected, prepared and analyzed. From the diffraction pattern, the composition of the sample is determined. It takes many minutes to analyze the data and provide the results. The X-ray detector views a small area, and so picks up only a small section of the diffracted X-rays. Thus, XRD analyzer developed with a curved detector is able to capture the complete diffracted pattern. This design allows XRD to be used for continuous monitoring and control [6]. This technique is highly developed and able to detect most cement minerals, even distinguish between the different phases of aluminates, belite and gypsum [6]. Unfortunately, it can only analyze a small sample specimen over a finite time to give an analysis. In addition, Dhanjal and Co-workers [6] further reported that this technique lacks the volume and timeliness of the data required for the control of clinker quality parameters real time.

C. Continuous On-Stream Mineral Analysis

XRD based on laboratory instruments analyze a very small amount of the material sample. Online XRD, on the other hand, analyzes significantly more material because a fresh stream of material is continuously passing under the X-rays. Dhanjal and Co-workers [6] reported that continuous XRD analysis provides the ability to control processes online, collects data real time and provides operators with a clear picture of the current and past performance of the process. Control actions can then be taken with live data, rather than using historical data as one would, if a sample had to be taken and analyzed in the laboratory. However, online XRDs are expensive to install and lack backup sensors in case they are faulty, down for maintenance or replacement. An attractive alternative to XRD is the use of soft sensor.

III. PROCESS MEASUREMENT AND CONTROL WITH SOFT SENSORS IN CEMENT MANUFACTURING PLANT

Many production processes require hours or even days to produce laboratory samples. During this time, out-of-specification products may have been produced. So, online predictive models that augment hardware instruments and laboratory analyses to provide real-time estimates of process and product conditions may be helpful. These predictive models that can provide the feedback and process information needed to keep production on track are called soft sensors.

A soft sensor is a mathematical model that correlates process state (i.e. process within specification or process out of specification) and product quality variables (such as composition, viscosity, etc.) that are difficult to measure online with frequently available process measurements (flows, temperatures, pressures, etc.). Soft Sensors can be easily integrated with control systems to provide tighter process performance [7]. A soft sensor provides real-time, accurate predictions of product quality variables, eliminating additional energy and production cost associated with out-of-specification products. Also, it can monitor processes, design tighter control, provide fault detection and diagnosis [8].

The major problem in all industries including the cement manufacturing industry is the lack of real-time measurement of product and process characteristics [9]. The unavailability of online measurement of important process variables can lead to out of specifications production. In the industry, an infrequent process sample (once per hour, once per 8 hour shift, once per day) which may not represent the entire process, is usually taken to the laboratory and (depending on the reference standard being used in the laboratory) the final result with typical delays of between 20 minutes to 1 week will require a minimum of three laboratory results before control actions are taken [9]. Soft sensors, otherwise called predictive sensors, inferential sensors, virtual sensors, and observer-based sensors [10] can provide low cost alternative to expensive online analyzer, provide real-time estimation of quality variable and can handle time delay associated with the slow sampling rate of laboratory equipment [8]. Soft sensor models can be classified as first principle models, data-driven models and hybrid models [8].

A. First Principle Models

The first principle models (FPMs) or white box models are obtained by deriving mathematical equations describing the physicochemical processes taking place in the system. Industrial processes are often very complex. So, according to Dražen and Co-workers [11], this approach offers great insight into the process (and the models can be extrapolated outside the operating conditions used to build them), but it is often impractical, time-consuming, requiring great process knowledge, effort, often results in insufficiently accurate model parameters and sometimes it is even impossible. Despite these challenges, efforts have been made to model cement rotary kiln (from first principles) for the purpose of control and optimization [13] and to better understand the processes taking place inside the rotary kiln [13], [14], [15], and [16]. However, no work has been published on developing mathematical models from first principles for sensing clinker quality parameters. Moreover, the available FPMs of cement rotary kiln contain variables that are not measurable real-time and consist of several nonlinear differential-algebraic equations which must be solved numerically. Hence, the available FPMs are not in the form suitable for online implementation as soft sensors for clinker quality parameters.

B. Data-Driven Models

Data-driven (black-box or empirical) models, are developed from data acquired during the process operation. This approach is used whenever there is not enough a-priori knowledge about the process. This modeling approach generally produces models which better describe the input-output relationship than first principle models [11]. These models can be developed quickly and cheaply because modern measurement techniques enable a large amount of operating data to be collected, stored and analyzed [8], [17]. However, the accuracy of these models depends on the quality of the historical data used to build them. Also, the accuracy may deteriorate due to outliers, noise and missing data [8].

Methods that are traditionally used for soft-sensor model development are: multivariate statistical methods, artificial neural networks and support vector machines [11]. In the production of cement, the quality of the clinker determines the quality of the cement. Attempts have been made over the years to develop artificial neural network (ANN) based soft sensor [17], [18], multivariate statistical based soft sensor [19] and support vector regression (SVR) based soft sensor [20] for online estimation of product quality in cement plants. However, the challenge with these models is that their accuracy depends largely on the quality of the historical data obtained from the rotary kiln. Experiments can be performed on the real plant to capture wider ranges of operating conditions, but Plant Managers rarely will allow deliberate changes to the operating conditions of the plant. Hence, one cannot extrapolate beyond the boundaries for which these soft sensor models were developed. Therefore, if the process drifts slightly outside the operating conditions used to build the soft sensor, the soft sensor will fail and requires reconstruction.

C. Hybrid Models

Hybrid model or grey-box model combines the strength of both first principle model and data-driven model [8]. In the development of this model, theoretical knowledge (from physical, mass and energy conservation laws) are combined with experimental data (from real plant experimentations, regular process operation) and/or experience from qualified process operators. Sadighi and Co-workers [16] developed a semi-empirical model for estimating the coating thickness in the burning zone of a cement rotary kiln. However, there are no published works on the use of hybrid model for sensing clinker quality parameters.

IV. CONCLUSION

The workability and strength of cement depend on the quality of the clinker produced from the rotary kiln. The quality of the clinker is dependent on the values of parameters such as the lime saturation factor (LSF), silica moduli (SM), alumina moduli (AM), alite (C_3S), etc. In this paper, the current measurement and estimation methods for cement clinker quality parameters were reviewed. The laboratory based (offline) techniques were found to lack the necessary accuracy, as they can only analyze a small sample specimen over a finite time to give an analysis. In addition, they lack the volume and timeliness of the data required for the control of clinker quality parameters real time.

Moreover, the existing online analyzers (hardware sensors) are expensive to install and lack backup sensors in case they are faulty, down for maintenance or replacement. The review shows further that soft (model or software-based) sensors are capable of offering solutions to some of the challenges of the online hardware sensors. However, their predictions depend on the hardware sensors for some input data. Moreover, the available cement rotary kiln models are not in the form suitable for online estimation of clinker quality parameters. The study therefore concludes that real-time measurement/estimation and control of clinker quality parameters is still a challenge in the cement manufacturing industry. It is therefore recommended that the instrument manufacturers for the cement manufacturing industry should strive to develop more measurement delay-free offline techniques and/or less expensive continuous online analyzers for effective measurement and control of cement clinker quality parameters. Moreover, soft sensor should be introduced to complement the online (analyzers) hardware sensors.

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